



Worries and Hopes for SUSY in CKM Physics: The $b \rightarrow s$ Example

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We discuss the twofold rôle of flavor and CP violation as a constraint in model building and as a signal of SUSY. Considering as an example $b \rightarrow s$ transitions, we analyze present bounds on SUSY parameters, discuss possible deviations from SM predictions in B_d and B_s physics and present strategies to reveal SUSY signals in present and future experiments in the CKM domain.

1 Introduction

Right since the advent of SUSY in the phenomenological arena in the early 80s, we have witnessed the presence of a twofold attitude of SUSY searchers towards FCNC and/or CP violation: on one hand, FCNC rare processes constitute a severe naturalness threat to low-energy SUSY extensions of the SM (i.e., the so-called flavor and CP violation problem of low-energy SUSY), whilst on the other hand they represent a promising way to reveal the presence of new physics through the effects of virtual SUSY particles running in the loops (and, in any case, they constitute the most powerful tool we have at disposal to constrain the enormous 124-parameter space of MSSM).

Concerning the former aspect, namely the FCNC threat, it is clear that in these last 20 years we saw an increased success of the CKM flavor pattern of the SM in reproducing the broad variety of flavor physics data. The combined experimental and theoretical precisions that we achieved have allowed for an enhanced confidence in the SM as the correct explanation for all the observed rare processes so far. As for possible SUSY contributions to observed FCNC and/or CP violation phenomena, they have to represent a small perturbation of the main bulk contribution represented by the CKM SM physics [1]-[6] (alternatively, it is still conceivable that we could have some very large new physics contribution, but then a strong conspiracy in exactly reproducing the SM expectations should be invoked [7]). The goodness of the SM Unitarity Triangle fit naturally poses a challenging question for new physics, namely should we ask for its complete flavor blindness to avoid unnatural fine-tunings in coping with the flavor problem?

We think that it is premature to answer positively to the above question. Indeed, no matter how good the UT fit looks so far within the SM, we believe (and, indeed, well substantiate such faith providing a few examples also in this talk) that there still exists a relatively ample space for new physics departures from the SM expectations in flavor physics. In other words, one should not forget that as useful as the UT approach proves to be in encoding a large amount of information concerning flavor physics, one should not overestimate its power in constraining new physics effects. For instance, a closer look at the UT fit reveals that new physics contributions to $s \rightarrow d$ and $b \rightarrow d$ transitions are strongly constrained, while new contributions to $b \rightarrow s$ transitions do not affect the fit at all, unless they interfere destructively with the SM amplitude for $B_s - \bar{B}_s$ mixing, bringing it below the present lower bound of 14 ps^{-1} [8].

Hence, we consider strict low-energy flavor blindness a too strong constraint. We think that it might be more advisable to insist on a high-energy flavor blindness, namely flavor universality of the soft breaking terms at the high energy scale where they show up in supergravity theories. Such weak form of flavor blindness is by no means equivalent to the strong requirement of low-energy flavor universality. In the long running path from the superlarge scale at which the SUSY soft breaking terms appear (presumably close to the Planck scale) down to the electroweak scale, many factors can give rise to even severe departures from flavor blindness of the low-energy structure of the soft breaking terms. A clear example of such difference between weak and strong flavor blindness arises in SUSY-GUTs where the large mixing(s) in the neutrino sector may imply the presence of large mixing angles in the right-

handed down-type quarks in spite of the initial flavor universality of the soft breaking terms at scales above the GUT scale [9,10].

As we mentioned above there is also the half-full glass perspective when looking at the increased experimental and theoretical accuracy in FCNC and CP violating processes and at its consequences for low-energy SUSY. We are now in a situation allowing us to be optimistic on the prospects to single out new-physics FCNC contributions in the present and coming experiments on rare decays. If this is certainly true for Lepton Flavor Violating (LFV) processes, (we all know well that observing one muon radiatively decaying into an electron would be an unquestionable signature of new physics), this is becoming true for the more difficult hadronic sector where theoretical and experimental intricacies often hinder the efforts to clearly disentangle new physics effects from the SM background. In this contribution to the CKM Workshop we will try to put all the above considerations into play considering the particularly interesting sector of the $b \rightarrow s$ transitions.

2 SUSY effects in $b \rightarrow s$ transitions

We now briefly report the results of the analysis of ref. [11], which aims at determining the allowed regions in the SUSY parameter space governing $b \rightarrow s$ transitions, studying the correlations among different observables and pointing out possible signals of SUSY. The constraints on the parameter space come from:

1. The $\text{BR}(B \rightarrow X_s \gamma) = (3.29 \pm 0.34) \times 10^{-4}$ (experimental results as reported in [12], rescaled according to ref. [13]).
2. The CP asymmetry $A_{CP}(B \rightarrow X_s \gamma) = -0.02 \pm 0.04$ [12].
3. The $\text{BR}(B \rightarrow X_s \ell^+ \ell^-) = (6.1 \pm 1.4 \pm 1.3) \times 10^{-6}$ [12].
4. The lower bound on the $B_s - \bar{B}_s$ mass difference $\Delta M_{B_s} > 14.4 \text{ ps}^{-1}$ [12].

We have also considered BR's and CP asymmetries for $B \rightarrow K\pi$ and found that, given the large theoretical uncertainties, they give no significant constraints on the δ 's. For $B \rightarrow \phi K_s$, we have studied the BR and the coefficients $C_{\phi K}$ and $S_{\phi K}$ of cosine and sine terms in the time-dependent CP asymmetry. In this channel, the measured BR is somewhat larger than the SM prediction, which would slightly favour SUSY contributions. However, given the large errors, we prefer not to use it to constrain the SUSY parameter space in our analysis.

All the details concerning the treatment of the different amplitudes entering the analysis can be found in ref. [11]. In summary, we use:

i) $\Delta B = 2$ amplitudes. Full NLO SM and LO gluino-mediated matching condition [3], NLO QCD evolution [14,15] and hadronic matrix elements from lattice calculations [16]. See ref. [17] for a discussion of the impact of chargino-mediated contributions in $\Delta B = 2$ processes.

ii) $\Delta B = 1$ amplitudes. Full NLO SM and LO gluino-mediated matching condition [18,19] and NLO QCD evolution [20–22]. The matrix elements of semileptonic and radiative decays include α_s terms, Sudakov resummation, and the first corrections suppressed by powers of the heavy quark masses [23]. For non-leptonic decays, such as $B \rightarrow K\pi$ and $B \rightarrow \phi K_s$, we adopt BBNS factorization [24], with an enlarged range for the annihilation parameter ρ_A , in the spirit of the criticism of ref. [25]. This choice maximizes the sensitivity of the factorized amplitudes to SUSY contributions, which is expected to be much lower if the power corrections are dominated by the “charming penguin” contributions [26]. Another source of potentially large SUSY effects in $B \rightarrow \phi K_s$ is the contribution of the chromomagnetic operator which can be substantially enhanced by SUSY without spoiling the experimental constraints from $B \rightarrow X_s \gamma$ [27]. Indeed, the time-dependent asymmetry in $B \rightarrow \phi K_s$ is more sensitive to the SUSY parameters in the case of chirality-flipping insertions which enter the amplitude in the coefficient of the chromomagnetic operator. One should keep in mind, however, that the corresponding matrix element, being of order α_s , has large uncertainties in QCD factorization.

We performed a MonteCarlo analysis, generating weighted random configurations of input parameters (see ref. [28] for details of this procedure) and computing for each configuration the processes listed above. We study the clustering induced by the constraints on various observables and parameters, assuming that each unconstrained δ_{23}^d fills uniformly a square $(-1 \dots 1, -1 \dots 1)$ in the complex plane. The ranges of CKM parameters have been taken from the UT fit ($\bar{\rho} = 0.178 \pm 0.046$, $\bar{\eta} = 0.341 \pm 0.028$) [29], and hadronic parameter ranges are those used in ref. [11]. Concerning SUSY parameters, we fix $m_{\tilde{q}} = m_{\tilde{g}} = 350$ GeV and consider different possibilities for the mass insertions. In addition to studying single insertions, we also examine the effects of the left-right symmetric case $(\delta_{23}^d)_{LL} = (\delta_{23}^d)_{RR}$.

We stress that, having fixed the relevant SUSY masses and SM parameters, the analysis we perform varying a single δ_{23}^d and computing various observables is completely analogous to the standard UT analysis. In-

deed, $\text{Re } \delta_{23}^d$ and $\text{Im } \delta_{23}^d$ play exactly the same role as ρ and η in the SM UT fit: starting from a given (uniform) a priori distribution, the p.d.f. for $\text{Re } \delta_{23}^d$, $\text{Im } \delta_{23}^d$ and the observables we discuss is obtained using the experimental constraints detailed above.

The gluino-mediated $b \rightarrow s$ transitions in the MSSM had already been investigated by several authors [30]–[41] before the announcement of $S_{\phi K}$ negative and have been vigorously reassessed [42]–[47] after such results were announced last Summer. In particular in the works of refs. [45,46] the correlation between $B \rightarrow \phi K_s$ and $B_s - \bar{B}_s$ mixing has been investigated making use of the mass insertion approximation. In ref. [11] the level of accuracy was improved with the inclusion of NLO QCD corrections and lattice QCD hadronic matrix elements and also in the correlation of $b \rightarrow s$ related processes with the selection of the $\Delta B = 1$ and $\Delta B = 2$ phenomena outlined above. As for the evaluation of $B \rightarrow K\pi$ and $B \rightarrow \phi K_s$, ref. [46] adopts the BBNS factorization, but without discussing the possibly large Λ/M_b corrections. This may be the source of some quantitative difference on the RR contributions to $BR(B \rightarrow \phi K_s)$ between ref. [11] and refs. [45,46], as we will detail in next Section. As for the analysis of ref. [47], this is performed in the mass eigenstate basis taking a specific down squark mass matrix (as suggested in SUSY GUT’s where the large neutrino mixing is linked to a large $\tilde{b}_R \rightarrow \tilde{s}_R$ mixing). Comparing the results of refs. [11] and [47] in the case of RR dominance we find some discrepancy in particular in the case of large $(\delta_{23}^d)_{RR}$ (see below). Once again a potential source of discrepancy in constraining the δ_{23}^d ’s from $A_{CP}(B \rightarrow \phi K_s)$ is represented by the delicate evaluation of the matrix elements of the chromo-dipole operators.

In fig. 1 we display the p.d.f. in the $\text{Re}(\delta_{23}^d)_{AB}$ – $\text{Im}(\delta_{23}^d)_{AB}$ plane in the single insertion case. Here and in the following plots, larger boxes correspond to larger numbers of weighted events. Constraints from $BR(B \rightarrow X_s \gamma)$, $A_{CP}(B \rightarrow X_s \gamma)$, $BR(B \rightarrow X_s \ell^+ \ell^-)$ and the lower bound on ΔM_s have been applied, as discussed above. The darker regions are selected imposing the further constraint $\Delta M_s < 20 \text{ ps}^{-1}$ for LL and RR insertions and $S_{\phi K} < 0$ for LR and RL insertions. For helicity conserving insertions, the constraints are of order 1. A significant reduction of the allowed region appears if the cut on ΔM_s is imposed. The asymmetry of the LL and LR plots is due to the interference with the SM contribution. In the helicity flipping cases, constraints are of order 10^{-2} . For these values of the parameters, ΔM_s is unaffected. We show the effect of requiring $S_{\phi K} < 0$: it is apparent that a nonvanishing $\text{Im } \delta_{23}^d$ is needed to meet this condition.

In figs. 2–3, we study the correlations of $S_{\phi K}$ with $\text{Im}(\delta_{23}^d)_{AB}$ and $A_{CP}(B \rightarrow X_s \gamma)$ for the various SUSY

insertions considered in the present analysis. The reader should keep in mind that, in all the results reported in figs. 2–3, the hadronic uncertainties affecting the estimate of $S_{\phi K}$ are not completely under control. Low values of $S_{\phi K}$ can be more easily obtained with helicity flipping insertions, in particular in the RL case. A deviation from the SM value for $S_{\phi K}$ requires a nonvanishing value of $\text{Im}(\delta_{23}^d)_{AB}$ (see figs. 2 and 4), generating, for those channels in which the SUSY amplitude can interfere with the SM one, an $A_{CP}(B \rightarrow X_s \gamma)$ at the level of a few percents in the LL and $LL = RR$ cases, and up to the experimental upper bound in the LR case (see fig. 3).

Finally, fig. 4 contains the same plots as fig. 1–2 in the case of the double mass insertion $(\delta_{23}^d)_{LL} = (\delta_{23}^d)_{RR}$. In this case, the constraints are still of order 1, but the contribution to ΔM_s is huge, due to the presence of operators with mixed chiralities. This can be seen from the smallness of the dark region selected by imposing $\Delta M_s < 20 \text{ ps}^{-1}$.

3 Where to look for SUSY

A crucial question naturally arises at this point: what are the more promising processes to reveal some signal of low energy SUSY among the FCNCs involving $b \rightarrow s$ transitions? For this purpose, it is useful to classify different “classes of MSSM” according to the “helicities” LL , RR , etc, of the different δ_{23}^d ’s.

The BaBar and BELLE Collaborations have recently reported the time-dependent CP asymmetry in $B_d(\bar{B}_d) \rightarrow \phi K_s$. While $\sin 2\beta$ as measured in the $B \rightarrow J/\psi K_s$ channel is 0.734 ± 0.054 (in agreement with the SM prediction [12]), the combined result from both collaborations for the corresponding $S_{\phi K}$ of $B_d \rightarrow \phi K_s$ is -0.39 ± 0.41 [48] with a 2.7σ discrepancy between the two results. In the SM, they should be the same up to doubly Cabibbo suppressed terms. Obviously, one should be very cautious before accepting such result as a genuine indication of NP. Nonetheless, the negative value of $S_{\phi K}$ could be due to large SUSY CP violating contributions. Then, one can wonder which δ ’s are relevant to produce such enhancement and, even more important, which other significant deviations from the SM could be detected.

3.1 RR and LL cases

We start discussing the RR case. As shown in Fig. 2 (upper right), although values of $S_{\phi K}$ in the range predicted by the SM are largely favoured, still pure δ_{RR} insertions are able to give rise to a negative $S_{\phi K}$ in agreement with the results of BaBar and BELLE quoted above. On this point we seem to agree with the conclusions of ref. [47], while being in disagreement

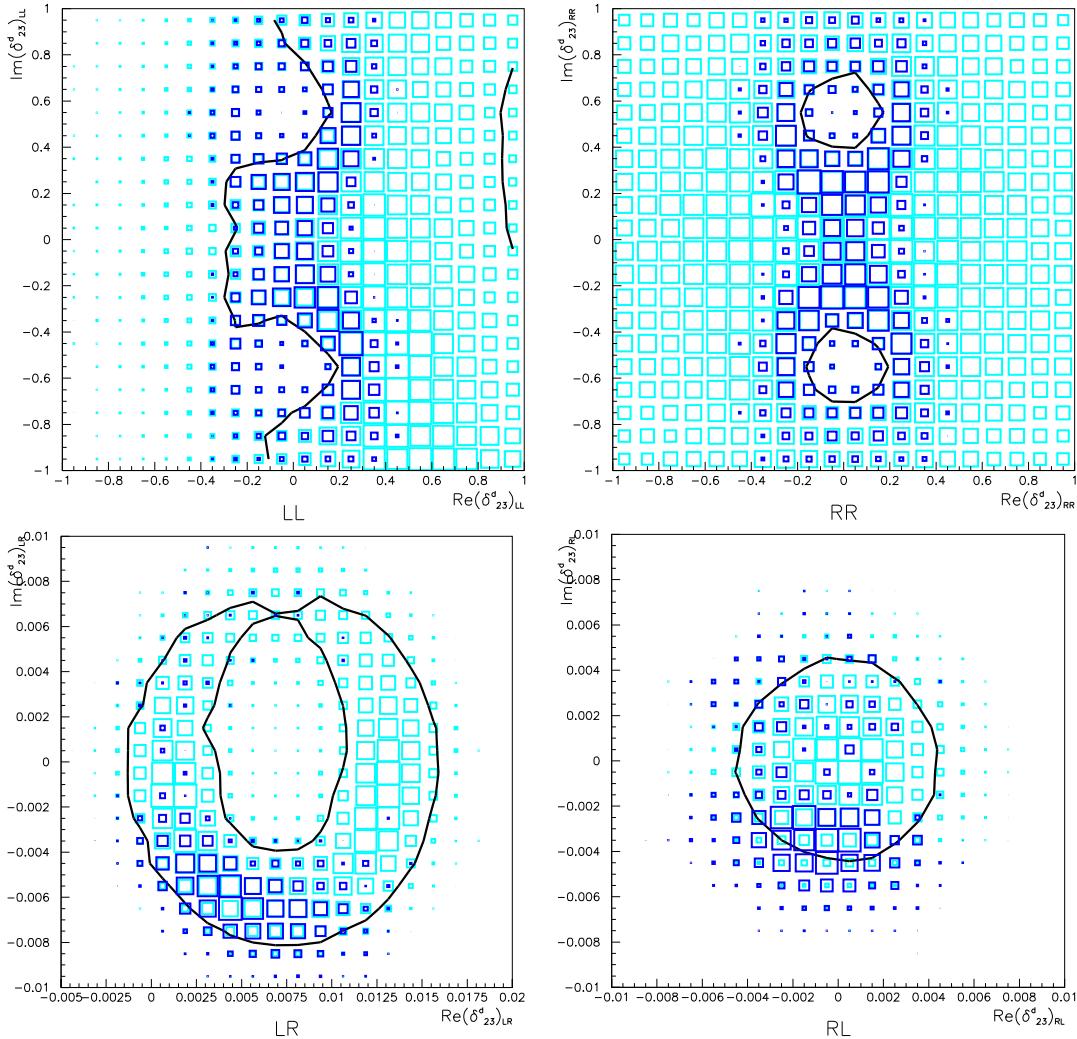


Figure 1. Allowed regions in the $\text{Re}(\delta_{23}^d)_{AB}$ – $\text{Im}(\delta_{23}^d)_{AB}$ space for $AB = (LL, RR, LR, RL)$. The black line contains 68% of the weighted events. The darker regions are selected imposing $\Delta m_s < 20 \text{ ps}^{-1}$ for LL and RR insertions and $S_{\phi K} < 0$ for LR and RL insertions.

with refs. [46] and [45]. As for the $B_s - \bar{B}_s$ mixing, the distribution of ΔM_s is peaked at the SM value, but it has a long tail at larger values, up to $\sim 120 \text{ ps}^{-1}$ for our choice of the range of δ_{RR} . In addition, we find that the expected correlation requiring large ΔM_s for negative $S_{\phi K}$ is totally wiped out by the large uncertainties (see fig. 5, lower right). In this respect, we are at variance with ref. [47], where it was emphasized that if the RR squark mixing yields the large deviation from the SM for the value of $S_{\phi K}$, then a huge contribution to the B_s mixing should necessarily follow making such oscillation unobservable at Tevatron. Hence, in the RR case it is possible to have a strong discrepancy between $\sin 2\beta$ and $S_{\phi K}$ whilst $B_s - \bar{B}_s$ oscillations proceed as expected in the SM (thus, being observable in the Run II of Tevatron). To conclude the discussion of the RR case, we expect the CP asymmetry in $B \rightarrow X_s \gamma$ to be as small as in the SM, while, differently from the SM, the time-dependent CP asymmetry in the decay channel $B_s \rightarrow J/\psi \phi$ is expected to be large.

We now move on to discuss the LL insertion. A major difference with the previous case concerns the SUSY contributions to $B \rightarrow X_s \gamma$. The LL insertion contributes to the same operator which is responsible for $B \rightarrow X_s \gamma$ in the SM and hence the SM and SUSY amplitudes interfere. As a consequence, the rate tends to be larger than the RR case and, moreover, a CP asymmetry can be generated up to 5% (see fig. 3, left). However, given the uncertainties, the correlation of $A_{CP}(B \rightarrow X_s \gamma)$ with $S_{\phi K}$ is not very stringent. As can be seen from the figure, negative values of $S_{\phi K}$ do not necessarily correspond to non-vanishing $A_{CP}(B \rightarrow X_s \gamma)$, although typical values are around

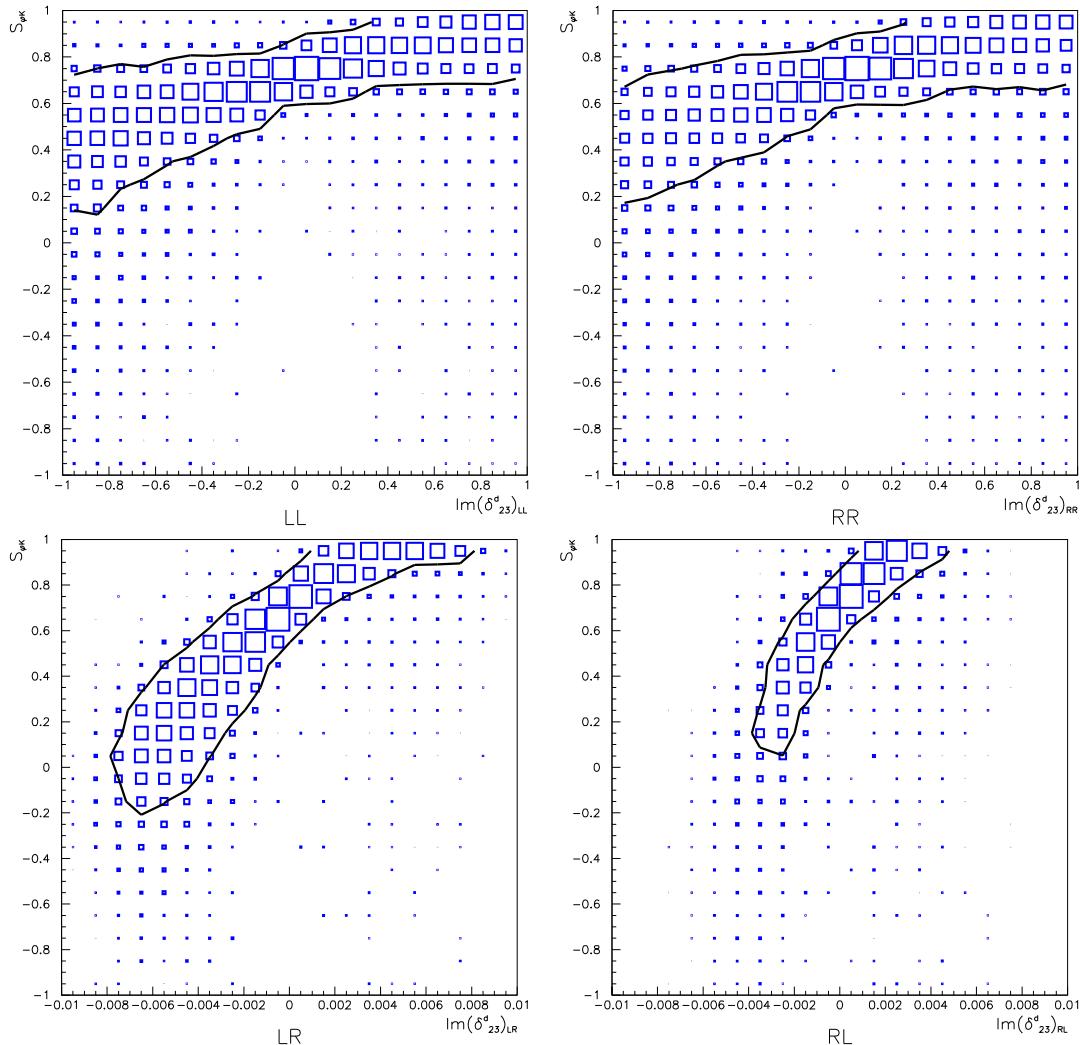


Figure 2. Correlations between $S_{\phi K}$ and $\text{Im}(\delta_{23}^d)_{AB}$ for $AB = (LL, RR, LR, RL)$. The black line contains 68% of the weighted events.

2%. Also, the constraint coming from the present measurement of the CP asymmetry is not very effective, as can be seen for instance from the distribution of ΔM_s in fig. 5 which is quite similar to the RR case. Finally, one expects also in this case to observe CP violation in $B_s \rightarrow J/\psi\phi$ at hadron colliders.

3.2 LR and RL cases

In these cases negative values of $S_{\phi K}$ can be easily obtained (although a positive $S_{\phi K}$ is favoured, cfr. Fig. 2, bottom row). The severe bound on the LR mass insertion imposed by $\text{BR}(B \rightarrow X_s\gamma)$ (and $A_{CP}(B \rightarrow X_s\gamma)$ in the LR case) prevents any enhancement of the $B_s - \bar{B}_s$ mixing as well as any sizeable contribution to $A_{CP}(B_s \rightarrow J/\psi\phi)$.

Notice that the LR mass insertion contributes to $b_R \rightarrow s_L\gamma$, much like the SM. The interference with

the SM amplitude produces the 'hole' in fig. 1, lower left. $A_{CP}(B \rightarrow X_s\gamma)$ as large as 5–10 % is attainable in this case (Fig. 3, upper right), offering a potentially interesting hint for NP. On the contrary, the RL mass insertion contributes to $b_L \rightarrow s_R\gamma$ and thus it does not interfere. Consequently, the CP asymmetry is as small as in the SM.

3.3 Double mass insertion: $(\delta_{23})_{LL} = (\delta_{23})_{RR}$ case

The main feature of this case is the huge enhancement of ΔM_s which is made possible by the contribution of the double insertion LL and RR in the box diagrams to operators with mixed chiralities (Fig. 5, lower left). Differently from all the previous cases, we are facing a situation here where $A_{CP}(B \rightarrow \phi K_s)$ at its present experimental value should be accounted for by the pres-

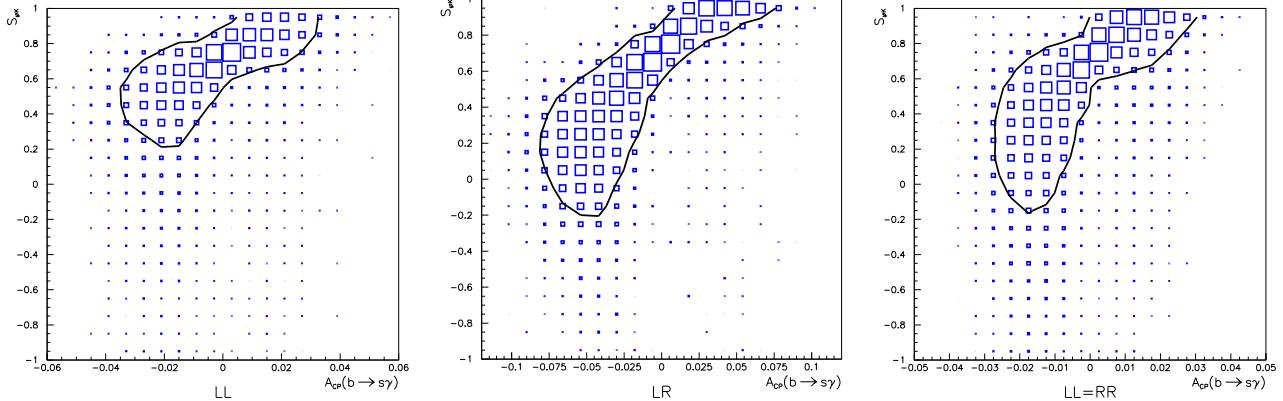


Figure 3. Correlation between $S_{\phi K}$ and $A_{CP}(b \rightarrow s\gamma)$ for SUSY mass insertions $(\delta_{23}^d)_{AB}$ with $AB = (LL, LR, LL = RR)$. The black line contains 68% of the weighted events.

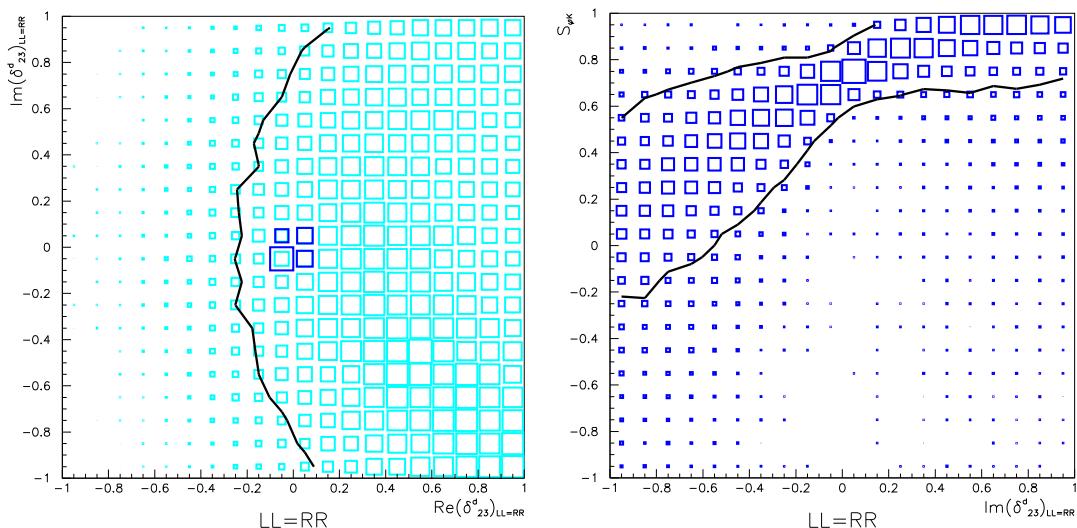


Figure 4. Same as in figs. 1–2 for the double insertion case $LL = RR$. The black line contains 68% of the weighted events. The darker region in the plot on the left is selected imposing $\Delta m_s < 20 \text{ ps}^{-1}$.

ence of SUSY, while ΔM_s could be so large that the $B_s - \bar{B}_s$ mixing could escape detection not only at Tevatron, but even at BTeV or LHCb. Hence, this would be a case for remarkable signatures of SUSY in $b \rightarrow s$ physics.

Finally, we remark that in the LR and RL cases, since for $m_{\tilde{g}} = m_{\tilde{q}} = 350 \text{ GeV}$ the constraints on the δ_{23}^d 's are of order 10^{-2} , the same phenomenology in $\Delta B = 1$ processes can be obtained at larger values of mass insertions and of squark and gluino masses, while contributions to $\Delta B = 2$ processes become more important for larger masses. In the remaining cases, where the limits on δ_{23}^d at $m_{\tilde{g}} = m_{\tilde{q}} = 350 \text{ GeV}$ are of order 1, the SUSY effects clearly weaken when going to higher values of sparticle masses.

Complementary information on SUSY contributions

to $b \rightarrow s$ transitions can be found in refs. [49,50], where chargino contributions to $A_{CP}(B \rightarrow \phi K_s)$ have been considered, and in ref. [51], where the correlation between SUSY contributions to $A_{CP}(B \rightarrow \phi K_s)$ and $A_{CP}(B \rightarrow \eta' K_s)$ have been discussed.

4 Outlook

Our results confirm that FCNC and CP violation in physics involving $b \rightarrow s$ transitions still offer opportunities to disentangle effects genuinely due to NP. In particular the discrepancy between the amounts of CP violation in the two B_d decay channels $J/\psi K_s$ and ϕK_s can be accounted for in the MSSM while respecting all the existing constraints in B physics, first of all the $BR(B \rightarrow X_s \gamma)$. The relevant question is then

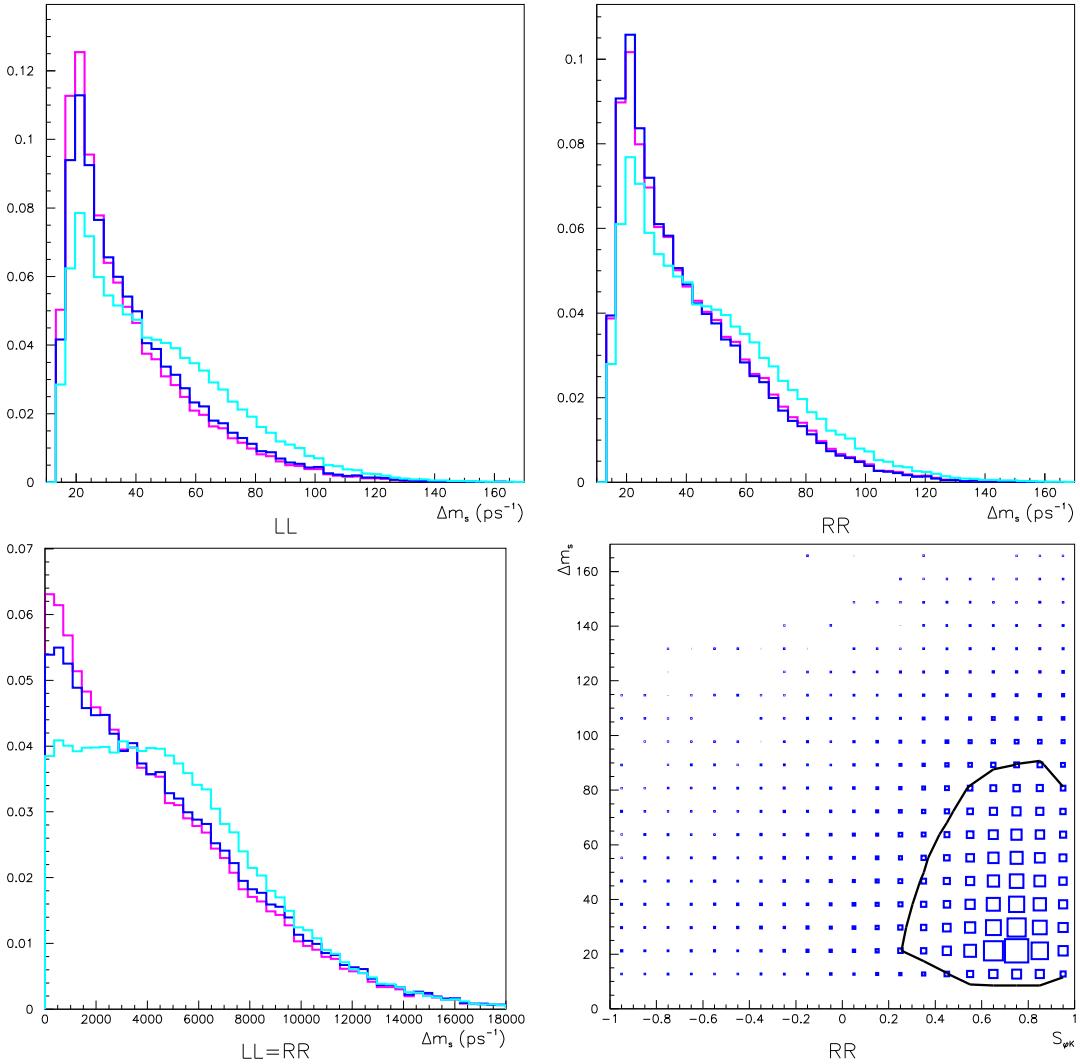


Figure 5. Distributions of ΔM_s for SUSY mass insertions $(\delta_{23}^d)_{AB}$ with $AB = (LL, RR, LL = RR)$. Different curves correspond to the inclusion of constraints from $B \rightarrow X_s \gamma$ only (magenta), $B \rightarrow X_s l^+ l^-$ only (cyan) and all together (blue). Lower right: correlation between ΔM_s and $S_{\phi K}$ in the RR case.

which processes offer the best chances to provide other hints of the presence of low-energy SUSY.

First, it is mandatory to further assess the time-dependent CP asymmetry in the decay channel $B \rightarrow \phi K_s$. If the measurement will be confirmed, then this process would become decisive in discriminating among different MSSM realizations. Although, as we have seen, it is possible to reproduce the negative $S_{\phi K}$ in a variety of different options for the SUSY soft breaking down squark masses, the allowed regions in the SUSY parameter space are more or less tightly constrained according to the kind of δ_{23}^d mass insertion which dominates.

In order of importance, it then comes the measurement of the $B_s - \bar{B}_s$ mixing. Finding ΔM_s larger than 20

ps^{-1} would hint at NP. RR or LL could account for a ΔM_s up to $\sim 120 \text{ ps}^{-1}$. Larger values would call for the double insertion $LL = RR$ to ensure such a huge enhancement of ΔM_s while respecting the constraint on $BR(B \rightarrow X_s \gamma)$. An interesting alternative would arise if ΔM_s is found as expected in the SM while, at the same time, $S_{\phi K}$ is confirmed to be negative. This scenario would favour the RL or LR possibility, even though all other cases but $LL = RR$ do not necessarily lead to large ΔM_s .

Keeping to B_d physics, we point out that the CP asymmetry in $B \rightarrow X_s \gamma$ remains of utmost interest. This asymmetry is so small in the SM that it should not be possible to detect it. We have seen that in particular with LR insertions such asymmetry can be enhanced

up to 10 % making it possibly detectable in a not too distant future.

Finally, once we will have at disposal large amounts of B_s , it will be of great interest to study processes which are mostly CP conserving in the SM, while possibly receiving large contributions from SUSY. In the SM the amplitude for $B_s - \bar{B}_s$ mixing does not have an imaginary part up to doubly Cabibbo suppressed terms and decays like $B_s \rightarrow J/\psi\phi$ also have a negligible amount of CP violation. Quite on the contrary, if the measured negative $S_{\phi K}$ is due to a large, complex δ_{23}^d mass insertion, we expect some of the above processes to exhibit a significant amount of CP violation. In particular, in the case of *RR* insertions, both the $b \rightarrow s$ amplitudes and the B_s mixing would receive non negligible contributions from $\text{Im } \delta_{23}^d$, while, if the *LR* or *RL* insertions are dominant, we do not expect any sizable contribution to B_s mixing. Still, the SUSY contribution to CP violation in the $B_s \rightarrow J/\psi\phi$ decay amplitude could be fairly large.

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